Power fluctuations from geographically diverse, grid coupled wind energy conversion systems

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POWER FLUCTUATIONS FROM GEOGRAPHICALLY DIVERSE, GRID COUPLED WIND ENERGY CONVERSION SYSTEMS

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I. Introduction

The coupling of wind energy converters(WEC) to the mains grid assuming high penetration rates raises the question whether power fluctuations will not impose prohibitive control action on conventional (fossil) power plants. This may occur at short time scales resulting in generation-load-mismatches. At long time scales the problem of surplus energy production from renewable sources may occur.

We have investigated into the power fluctuation characteristics of geographically diverse WEC systems both in the time and in the frequency domain on the basis of data from several North German sites.

II. Characteristics of Power Fluctuations in Wind Farms

In this section we will deal with the fluctuation characteristics of wind fields and the related power output fluctuations of WEC in the frequency domain of 1/1 sec down to 1/10 min. The spatial scale is described by separations of some 100 m (e.g. the size of a wind farm).

The power output fluctuations of wind farms in the referred frequency range are of importance e.g. for the operational behaviour of wind farm/diesel systems for small (island) grids. Generally the fuel saving of wind/diesel systems is to a high extent sensitive to the sub-hourly fluctuations of wind power. Performance improvements may be achieved for example by implementation of short term (some minutes') storage (Lipman et al. (1)). It is thus of importance if differences in high frequency behaviour can be detected between single site and farm output.

In the analysis of WEC systems distributed over large geographical areas wind farms will be treated as single generation units. This also calls for a model of the effective output fluctuations and the effective characteristics of the wind farm.

Micrometeorological basis

The properties of the turbulent wind field in the space and frequency scales considered here have been extensively covered by micrometeorological research. Unfortunately spatial separations were generally somewhat less than the spacings we investigated into. A review of some fundamental characteristics is given by Fordham (2). In the context discussed here we are mainly interested in the characteristics of the coherence of wind speed fluctuations. The standard model for the coherence is given by

$$coh = e^{-a \cdot n \cdot x/u}$$

where:
- n frequency
- x spatial separation
- u mean wind speed (here for averaging times in the range of 10 min to 1 h)
- a decay constant

The decay constant a is given in (2) as $a = f(x/z)$ (where z is the heigth above ground level) for the case of x lateral to the vector of the mean wind speed and near-neutral thermal stratification of the athmospheric boundary layer. For ratios of x/z as used in the following section values of $a = 50$ may be assumed.

We used this model for a semiquantitative look at the amount of smoothing of wind farm output as compared to single site fluctuations. It should be mentioned that the extension of the coherence model as given above to distances of some hundred metres is somewhat speculative.

Spectral characteristics of farm averaged windspeeds

We here discuss the fluctuation characteristics of a time series of wind speed that represents the averaged wind speed at hub height within a wind farm. The problems associated with the transfer of the wind field information to the power output characteristics of the wind farm will be discussed in the next section. Most of the theory displayed in this section will also apply to the investigations concerning the lower frequency scales.

For the topic of rotor disc averaging effects methods for the analysis of the average wind speed are outlined by Bossanyi (3) and Healey (4)

We assume the single point spectral power density of the wind speed fluctuations at any point in a farm to be given by the same $S_o(n)$. The total variance of these time series' is given by

$$\sigma^2 = \int S_o(n)dn$$

Assuming a symmetric cross-correlation function the cross-spectral density of the fluctuations at two points i, j is given by

$$S_{ij} = S_o(n) \cdot \sqrt{coh(n, x_{ij}, u)}$$

The spectrum of the average wind speed could then be calculated as

$$\begin{aligned} S_{ave}(n) &= \frac{1}{N^2} \cdot \Sigma\Sigma S_{ij}(n) \qquad (1) \\ &= \frac{1}{N^2} \cdot \Sigma\Sigma S_o(n) \cdot \sqrt{coh(n, x_{ij}, u)} \\ &= S_o(n) \cdot \frac{1}{N^2} \Sigma\Sigma \sqrt{coh(n, x_{ij}, u)} \\ &= S_o(n) \cdot F_{ave}(n) \qquad (2) \end{aligned}$$

For all values of coherence smaller than 1 the last term in this equation will represent a filter function acting on the single point spectrum. Especially for uncorrelated fluctuations (i.e. $coh = 1$ for $i = j$ and $coh = 0$ for $i \neq j$) the filter takes on the value of $\frac{1}{N}$ for all frequencies. Using the coherence model given in the last section the filter may be evaluated for any linear farm configuration . Fig. 1 gives an example of a comparison between single point, five-point-averaged spectrum and a spectrum processed by a $\frac{1}{5}$-filter. The characteristics of the single point spectrum we used are based on a standard model

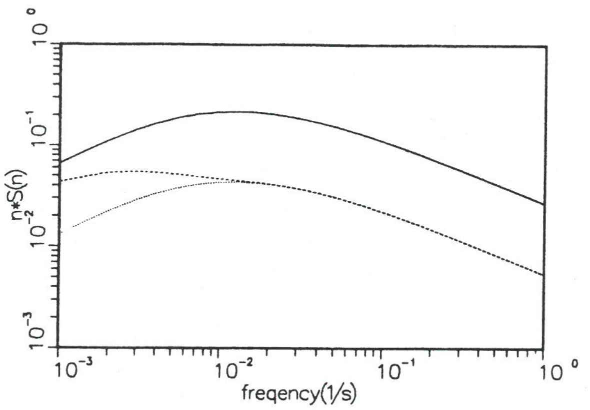

Fig. 1: Single point spectrum (solid line, u = 5m/s, z=20m; unit variance), spectrum for the farm averaged wind speed (dashed line, 5 WEC, linear array, spacing 60m) and $\frac{1}{N}$-filter processed for $N = 5$ (dotted line).

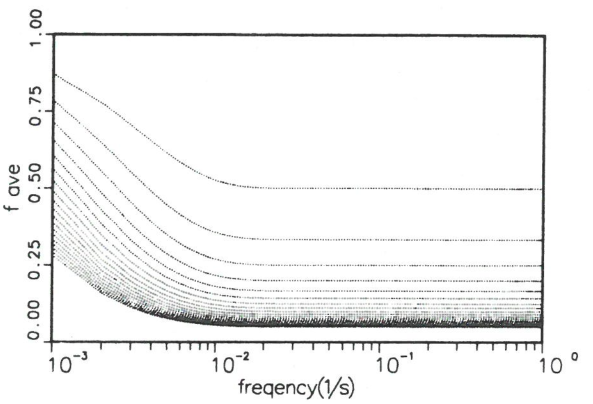

Fig. 2: Filter functions as produced from wind farms (straight line arrays) with various numbers of turbines (2 to 20) at a spacing of 60 m and a wind speed of 5 m/s. The values clearly approach 1/N at high frequencies.

(cf. for instance Madsen (5)). In fig. 2 some filter functions for linear farm layouts (u perpendicular to the echelon) with various numbers of turbines, a given spacing and wind speed are depicted. For a farm layout with 5 WEC, spacing of 60m (data of a farm with this configuration will be discussed later) and wind speeds of about 5 m/s fluctuations (measured in W) with frequencies higher than 10^{-2} Hz will be damped by a factor of $\frac{1}{\sqrt{N}}$ (reduction in power spectral density proportional to $\frac{1}{N}$).

Fluctuations in farm power output

The extrapolation of the characteristics of wind fluctuations to the power output fluctuations is complicated by the fact that wind turbine output generally displays a non-linear low pass response to the wind signal. For this reason a direct application of the abovementioned filter eqn. (2) to the power output spectrum is possible only for special cases.

For a WEC operating at constant rotational speed in a wind speed range where the power output is an allmost linear function of wind speed, the power output spectrum may be approximated by

$$S_P(n) \;=\; S_o(n) \cdot (\frac{dP}{dv})^2 \cdot F_{rot}(n) \qquad (3)$$

S_P is measured in W^2/Hz. dP/dv describes the power response to the wind speed and F_{rot} the low pass filtering by disc averaging effects. Under these assumptions eqn. (2) may be directly applied to the single point power output spectrum to obtain the spectral characteristics of wind farm output

$$S_\Sigma(n) \;=\; N^2 \cdot S_P(n) \cdot F_{ave}(n) \qquad (4)$$

with the special cases

$$S_\Sigma(n) \;=\; N^2 \cdot S_P(n) \qquad (5)$$

for $coh = 1$ and

$$S_\Sigma(n) \;=\; N \cdot S_P(n) \qquad (6)$$

for the case of uncorrelated power output series'.

The analysis of the power fluctuations becomes increasingly complicated if the non-linear response of the turbines for wind speeds near the cut-in and rated wind speed are considered. WECs operating with variable rotational speed moreover display more complex filter behaviour due to inertia of the machine and the characteristics of the control mechanisms. We can here only sketch out a method for handling these problems.

A valuable but computing-time intensive approach for a general treatment of the farm output fluctuations may be taken by a simulation scheme of time series' of wind speeds at the sites of the WECs using the Shinozuka approach (6). From these wind speed time series' the time series' of turbine output may be calculated using the differential equation describing the operational behaviour of the turbine with respect to all relevant non-linearities involved.

Results from measurements

The empirical data discussed here originate from a small wind farm with 5 WEC (16 m diameter, variable rotational speed; linear array with a spacing of 60m). This farm is described in more detail by Beyer et al. (7).

Fig. 3a and b give the comparison of the power spectra of the 5 single WEC to the spectrum of farm output. The spectra were calculated for time series' with a length of 2400 seconds (fig. 3a) and 1700 seconds (fig. 3b). The mean wind speed was 5.0 and 8.7 m/s respectively. The single turbine spectra shown constitute the average from the five single WEC data. The farm spectra are furthermore compared to spectra according to eqns. (5) and (6). It should be pointed out that for both time series' significant deviations, if any, from the 'uncorrelated' spectrum occur only at low frequencies. This is in reasonable accordance with the abovementioned theoretical filter functions.

Conclusions

It may be stated that both theory and measurement show that power fluctuations with frequencies higher than 10^{-2} Hz are levelled out in windfarms according to a $\frac{1}{N}$-filter (acting on S) at first approximation. Thus in the analysis of wind energy systems consisting of single wind farms with high numbers of turbines distributed over distances of some tens of kilometres the output of the farms may be treated as almost smooth in time scales of some minutes.

III. Characteristics of Power Output Fluctuations in Widely Spaced WEC-Systems

The following calculations are based on hourly time series' of wind speeds from five North-German sites (cf. map in fig. 4). These data cover the years 1982, 1985 and 1986. They ach lower maximum values in the frequency range considered. Here two facts have to be mentioned: the distance between Westermarkelsdorf and the other stations is greater than for all other stations; Westermarkelsdorf lies in the climatic region of the Baltic Sea whereas all other stations belong to the region of the German Bay in the North Sea. It may be shown that for all pairs of stations fluctuations above 1 / 5 hrs show very low coherence.

Correlation characteristics of wind speed fluctuations

For every pair of the five stations the cross-correlation coefficient for the complete data set was calculated. The results are given in fig. 7 together with a seasonal breakdown. The correlation-coefficient ρ is shown versus inter-station distance. As could be expected from the high values of coherence at frequencies lower than 1 / 48 hrs given in the above section correlation takes on high values that only decrease slowly with distance. Correlation for summer data is somewhat lower. On the other hand winter season correlation is higher due to coincidence in occurence of high wind periods.

As could be concluded from above section fluctuations in the frequency range over about 1/12 hrs should display decreased correlation. To demonstrate this we removed the trend from the time series' by substracting a 24-hour moving average. Fig. 8 shows the correlation characteristics of the residual time series. The values are remarkably decreased as compared to the original time series.

Hourly gradients in wind power production.

The fluctuations inherent in wind power production could lead to high requirements for power output control mechanisms in the conventional part of the grid. The low coherence of hourly fluctuations in wind speed over distances as represented by the stations under investigation, though, gives hope that these requirements may be limited. To demonstrate this effect the maximum hourly gradients of power output were calculated for the single sites and lumped power output. In these calculations a WEC power characteristic as shown in fig. 9 was assumed. The power output at the different sites is scaled in such a way that every site delivers the same mean power output. Wind speeds at measuring height of 10 m were used in these calculations. Fig. 10 shows the probability of occurence of power gradients of a certain level (normalized to the mean power output) at a single site and for lumped output. The occurence of high values of the power gradient is massively reduced in this example.

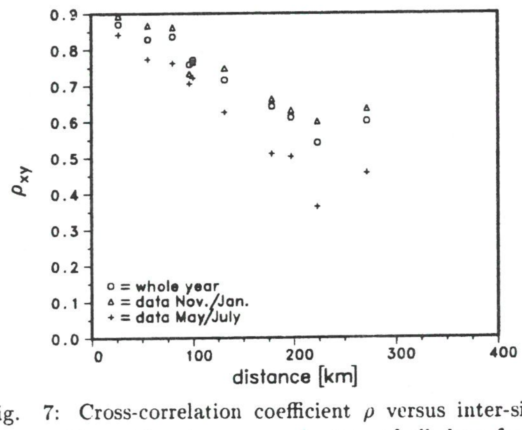

Fig. 7: Cross-correlation coefficient ρ versus inter-site distance. Ensembles show an evaluation of all data from the time series 1982-1985-1986 and seasonal excerpts.

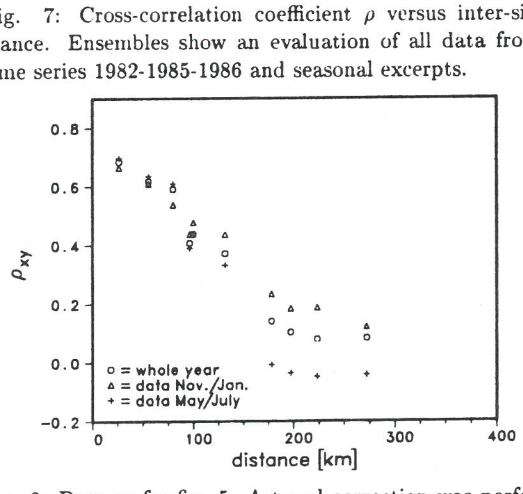

Fig. 8: Data as for fig. 5. A trend correction was performed by subtracting the 24-h-moving-average from all time series'.

Unutilizable or surplus energy

When penetration levels D (ratio of mean wind power to mean consumed power, $D=\bar{P}_{wind}/\bar{P}_{load}$) of some tens of percent are reached the converter system displays a rated capacity higher than the mean power consumption in the grid and in most cases also surpassing maximum load requirements. This raises the problem of production of unloadable power. The energy produced above the load power level has to be dumped unless storage systems are included in the grid. We calculated the share of surplus energy for systems with diverse converter sites as a function of penetration level. The load pattern used was that of the West-German utility grid in 1982 (ref. (8)). In these calculations we assumed that the conventional part of

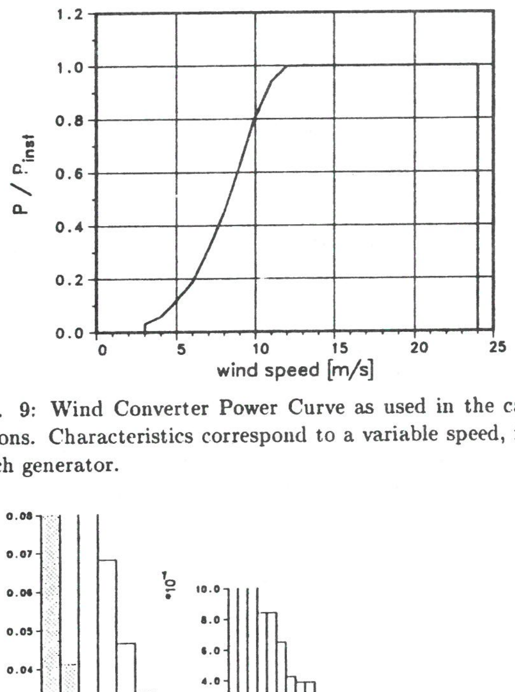

Fig. 9: Wind Converter Power Curve as used in the calculations. Characteristics correspond to a variable speed, fixed pitch generator.

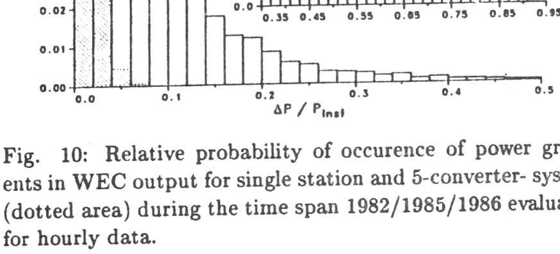

Fig. 10: Relative probability of occurence of power gradients in WEC output for single station and 5-converter- system (dotted area) during the time span 1982/1985/1986 evaluated for hourly data.

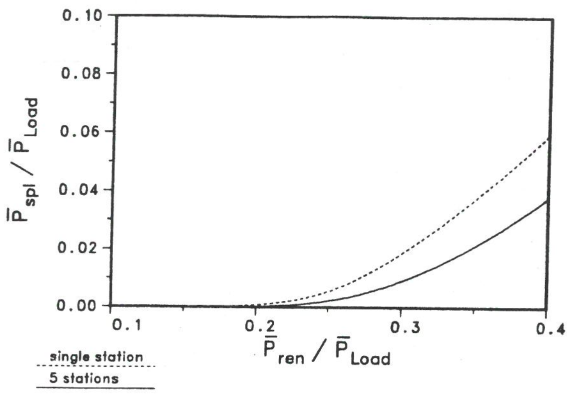

Fig. 11: Surplus power generated from single and multi converter systems.

the grid may be controlled in the full power range (i.e. no minimum loading of conventional power plants was taken into consideration).

Fig.11 gives the comparison of the surplus calculated from single point data and from a combination of five sites. The calculations are based on the power curve as given in fig. 9. The dispersal of WECs shows some beneficial effect but this is not very pronounced. This is mainly due to the high correlation in low frequency fluctuations. It should be noted that the surplus curves are sensitive to the selected characteristics of the wind turbines.

Acknowledgements

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